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Indicators for environmental sustainability

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Abstract

Decision making on sustainable consumption and production requires scientifically based information on sustainability. Different environmental sustainability targets exist for specific decision problems. To observe how well these targets are met, relevant environmental indicators are needed. In this study, we reviewed indicators applied in life cycle assessment (LCA), planetary boundary framework (PB), and Sustainable Development Goals (SDGs) developed under United Nation. The aim is to 1) identify their applications and relevant decision context; 2) Review their indicators and categorize them into Drivers-Pressures-States-Impacts-Responses scheme for comparison and; 3) provide suggestions for indicator system choice and important aspects to consider when choosing.

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Keywords: decision support; indicator; sustainability; metrics; environmental targets; life cycle assessment; planetary boundary; Sustainable Development Goals

1. Introduction

Sustainability is to "meet the needs of the present without compromising the ability of future generations to meet their own needs."[1] When a decision involving sustainability aspects needs to be made, it requires scientifically based information on sustainability. This has been a new challenge for providing rational, coherent and transparent decision support towards sustainable consumption and production pattern. Human behavior and societal context play a larger role in social and economic sustainability, where little consensus exist. The environmental pillar addresses the ecosystems and their life support functions for mankind. Here assessments can be based on environmental science with a higher degree of predictability and scientific consensus. This study will focus on environmental sustainability assessment.

The concept of sustainability comes from different roots, such as ecological carrying capacity, resource reserve, and critique of technology [2]. Each of these research areas has its own roots and thus unique targets, e.g. staying below ecological carrying capacity, not deplete resource reserves and minimize impacts from technology development. To observe how well those targets are met, relevant indicators and corresponding assessment methods have been developed.

In this study, we reviewed some broadly used methodologies and their corresponding indicators, including the ones in planetary boundaries (PBs), Life Cycle Assessment (LCA), and Sustainable Development Goals (SDGs). These indicators are then classified into different impact categorizes. The differences and similarities are analyzed as background for a discussion of important aspects to be considered when choosing indicators for environmental sustainability.

2. Sustainable environmental indicators in different fields

There are three essential questions that needs to be addressed and answered when considering sustainability of an activity or system [3]: 1) What is the system to be protected? Where is the system boundary? 2) What is the time scale? 3) What is system quality that will be maintained or improved? The system quality can be assessed via indicators and corresponding methods. The indicators are a simple way to answer "How might I know objectively whether things are getting better or getting worse?" [4]. For each of the indicators, a baseline is often used to express the "standard quality" that needs to be maintained or the target that needs to be reached if it is not there yet. Due to different purposes, the

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answers to the three essential questions are also different in each methodology, which also appears to be the key information for specific decision problem. In this section, we will introduce the three focused environmental sustainability assessment methods and their indicators, addressing answers to the three essential questions.

2.1. Planetary boundaries

PB "defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the stability of the earth system" [5]. By estimating impacts towards PB, it aims at protecting the functioning of the earth system within an "ethical time horizon- short enough to influence today's decisions yet long enough to provide the basis for sustainability over many generations to come" [6]. Several key processes are identified and some methods were developed to quantitatively express the boundary level that should "not be transgressed if we are to avoid unacceptable global environmental change" [6]. With its focus on the stability of Earth system processes, the PB approach is concerned with impacts on the natural environment and does not intend to reflect impacts to human health. Nine planetary boundaries were recognized so far as shown in Table 1. For each of the boundaries, one or more indicators have been developed to show the distance to the boundary and indicate when we are at risk to transgress it. Since PB is a rather new concept, methods for assessing some of the indicators are still under development and thus not mature yet. Large uncertainties of the boundaries are expected, where more research is needed [5]. However, the PB approach provides a way to assess environmental impacts against an absolutely scale, taking the whole earth as the system boundary.

2.2. Life Cycle Assessment

LCA "quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services" [7]. It is a mature and robust method that comes with ISO standard (ISO 14040/14044). LCA firstly quantifies the emissions from all life stages of a product or service. The impacts caused by the emissions are then assessed by Life Cycle Impact Assessment (LCIA) methodologies. The intention of LCA is to compare alternatives. Therefore it only expresses environmental impacts in relative terms, e.g. which option is more environmental friendly. It cannot judge if the solution is sustainable in absolute terms since it doesn't relate to an absolute boundary as PB does. The focus of LCA is global as for PB, but some of the impacts are modelled at a regional scale when this is relevant. The environmental quality that can be affected is expressed by a set of impact categories, each represented by one or more indicators. There are many LCIA methodologies available (e.g. ReCiPe, IMPACT 2002+, etc.), where noticeable differences exist in coverage of impacts, in choice of indicators for some impact categories and in the environmental models applied to model the indicators. After a joint effort of reviewing those methods, recommendations of best practices were identified [8]. There 13 separate cause-effect chains were identified from emission to damages on the area of protection (natural environment, human health and natural resources). Each of them has one or more midpoint indicator located somewhere in the chain between emissions and damages, where endpoint indicators are located (Table 1). The environmental sustainability of an activity can thus be judged either by midpoint indicators, or endpoint indicators. New impact categories such as noise, accidents and salination are also under development. The corresponding time scale is different depending on the impact category, ranging from years (e.g. acidification, eutrophication and ecotoxicity) to very long time scales (e.g. climate change, ozone depletion, fossil and mineral depletion) [9].

2.3. Sustainable Development Goals

Many environmental targets and indicators exist in regulatory context, to promote regulators making decisions towards a livable and sustainable place for humans. They present a perspective from human-centered society. There is an abundance of such targets and indicators at different decision levels. Among them, SDGs are the most recent ones released by UN. They are part of a plan of action to stimulate all nations to "heal and secure our planet" and "shift the world on to a sustainable and resilient path" [10]. 17 goals supported by 169 targets were established in SDGs to be attained by 2030 [10]. To facilitate the implementation and monitoring of the SDGs, Sustainable Development Solution Network was launched by the UN to develop indicators. Indicators have been and will be further developed under each target for monitoring and assessment purposes [11]. The SDGs target to assure common goals and understandings between different stakeholders (e.g. policy-makers, local residents and business partners) in the development of a sustainable world.

Depending on the application context, the system boundary that is considered under the SDGs is often within a certain region or nation, but some of them are also global. Most of the targeted indicators have to reach a certain level within a limited time. In addition to the strong focus of achieving environmental sustainability, a strengthening of technology transfer, capacity-building in the developing countries and promotion of local public awareness have been emphasized in SDGs to facilitate the achievement of these targets.

3. Classification and comparison of environmental sustainability indicators

In order to support a comparison of the environmental indicators in LCA, PB and SDGs, a summary of the proposed indicators is given in Table 1. To better understand the relationships between different environmental sustainability indicators in different domains, each relevant indicator is classified into a specific impact type of environmental impact. Under each impact type, the indicators are further categorized by applying a widely used flexible framework for relating human activities to environmental status: Driver-Pressure-State-Impact-Response (DPSIR) scheme as shown in Figure 1 [12]. It starts with “driver”, which reflects the need of e.g. individuals and industries. The drivers lead to human activities that invoke “pressures” on the environment. As a result of the pressures, the “state” of the environment is changed and this may cause an “impact” on the environment, which may eventually trigger a political “response” [12].

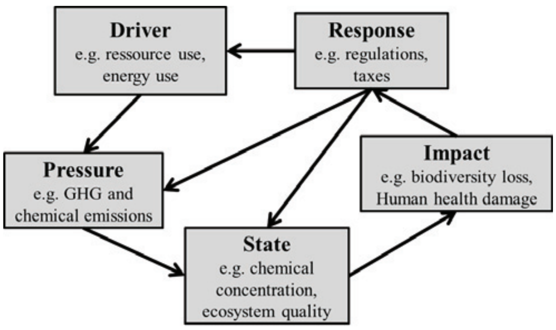

Figure 1. The DPSIR framework, adapted from EEA [12]

Six PB indicators are categorized as State indicators, and two are Pressure indicators. In one category (introduction of novel entities), PB does not have a defined indicator. PB covers in total nine impact categories (Table 1). Similarly, 11 LCA midpoint indicators are State indicators, while only one is considered as a Pressure indicator (Freshwater use). All LCA midpoint indicators contribute to at least one of the three LCA damage indicators, which are classified as Impact indicators in the DPSIR framework. Driver, Pressure and Response indicators are easier to regulate, but their environmental relevance is more indirect. In comparison, State and Impact indicators are more objective and robust in the sense that they represent the consequences of the others on the status of the environment. This explains why scientists set up planetary boundaries mainly via states indicators, and LCA compares environmental performance at states and impacts level. In contrast, SDGs aim at providing guidelines for regulations, and they have to encompass as many driver and response indicators as needed to fulfil the very wide purpose. Therefore, SDGs covers the most impact categories (16 out of 19). In addition to States and Impacts indicators, they provide Pressure, Driver and Response indicators in six, six and eight categories respectively. The Driver indicators under the SDGs represent the growing focus of societal development on increasing efficiency/intensity in energy use, water use, CO_2 emissions, nitrogen and phosphorus use. Response indicators focus on how governance can facilitate sustainability, via providing support, proper management, strategies, subsidies and promoting or restricting certain technologies.

There are seven of the environmental impact categories that are covered by all three indicator sets (Table 1). Among those, climate change and freshwater use show most consensuses in terms of applied cause-effect chain. For climate change, greenhouse gas (GHG) emission (Pressure) causes change in GHG concentration (State). Similarly for freshwater, water use is the Pressure and the proportion of water resource that has been used is the State. Response indicators on management and strategies are identified to regulate the intensity of GHG emission or efficiency of water use (Driver). For both impact categories, SDGs covers Driver, Pressure and Response indicators, reflecting the strong political emphasis. For eutrophication, the Pressures are clearly coming from nitrogen and phosphorus emissions. SDGs aim to regulate nitrogen and phosphorus efficiency (Driver). For chemical pollution, SDGs include indicators on chemical emission and concentration as the Pressure and State indicator respectively. This category is mentioned in PB, but yet no specific indicator is defined. For ozone depletion, PB and LCA have a similar State indicator related to ozone concentration in the stratosphere. SDGs operate with one Pressure indicator on the consumption of ozone depleting substances. For biodiversity and acidification, different States indicators exist, where a consensus is strongly needed. For all the impact categories mentioned above, some research has been done, but not enough to understand the full cause-effect chain, especially the connection between state and impacts.

There are several categories where only SDGs indicators exists, namely waste treatment, marine system change, fish resources, energy resources, and food and agricultural resources. State indicators are available for all the mentioned categories, but Pressure indicators only exist for two categories and Impact indicators are lacking for all of them. The lack of good understanding on cause-effect chain in these categories makes it difficult to judge how serious and urgent the problems are. For resources especially, a fair judgement on the reserves and renewability is essential to define the impacts and thus response indicators. Here the needs from regulators point to the direction of future research needs.

4. Discussion and proposals

Generally speaking, LCA and PB have similar perspectives. Their indicators are science-based, and operational methods are available for assessing most of them. In contrast, fewer details on the methodologies are available now for SDGs indicators. To supplement this, UNEP has organized several workshops to develop proposals and more are foreseen. For example, integrated environmental indicators were proposed to “support multiple goals and targets” [13]. To promote Sustainable Consumption and Production (SCP), a set of relevant indicators were developed [14]. Many indicators listed in SCP have not yet been included in the SDGs, e.g. biomass footprint of consumptions, rates of groundwater depletion, water footprint, material footprint, food waste at consumption stage and metal recycling rate [14]. As SDGs stepping into the operational stage, more guidelines and proposals are expected to provide operational measurements methods for the SDGs targets.

To choose the relevant indicators for decision support, it is necessary to understand the context of the indicators and the decision problem that is to be addressed. Traditionally, LCA is mainly operated on product systems. SDGs will mostly be operated on sector and national level, while PB aims at operating on regional and global level. Hence, indicators such as emission intensity, usage efficiency and management strategies that typically target the sector or national level via policies or regulations only appear in SDGs. However, these indicators are useful as guidance also for the smaller scale applications in companies or even products with indication of where SDGs aim to develop towards sustainability. In contrast, LCA only contains quantitative science-based State and Impact indicators, to be assessed on product and project level without interface to regulation and policies.

Table 1. Summary of environmental sustainability indicators in different area

Impacts on		Drivers	Pressures	States	Impacts	Responses
Climate change	LCA			- Radiative forcing as Global Warming Potential (GWP100)	- Ecosystem damages - Human health damages	
	PB			- Atmospheric CO_2 concentration - Energy imbalance at top-of-atmosphere		
	SDGs	- GHG emissions intensity of areas under forest management ($GtCO_2e$ / ha) - CO_2 intensity of new power generation capacity installed (gCO_2 per kWh), and of new cars (gCO_2/pkm) and trucks (gCO_2/tkm)	- Net GHG emissions in the Agriculture, Forest and other Land Use (AFOLU) sector (tCO_2e) - Total energy and industry-related GHG emissions by gas and sector, expressed as production and demand-based emissions (tCO_2e)		- Losses from natural disasters, by climate and non-climate-related events (in US$ and lives lost)	- [Climate Change Action Index] – to be developed - Implicit incentives for low-carbon energy in the electricity sector (measured as US$/MWh or US$ per ton avoided CO_2) - Availability and implementation of a transparent and detailed deep decarbonization strategy, consistent with the 2°C - or below - global carbon budget, and with GHG emission targets for 2020, 2030 and 2050. - [Disaster Risk Reduction Indicator] – to be developed
Acidification	LCA			- Land and water: Accumulated Exceedance	- Ecosystem damages	
	PB			- Ocean: carbonate ion concentration		
	SDGs			- Ocean acidity (measured as surface pH)		
Ozone depletion	LCA			- Ozone Depletion Potential (ODP)	- Human health damages	
	PB			- Stratospheric O_3 concentration		
	SDGs		- Consumption of ozone-depleting substances (MDG Indicator)			
Atmospheric aerosol loading	PB			- Aerosol Optical Depth (AOD)		
	SDGs			- Aerosol Optical Depth (AOD)		
Eutrophication	LCA			- Accumulated Exceedance	- Ecosystem damages	
	PB		- Global: P flow from freshwater into ocean - Regional: P flow from fertilizers to erodible soils - Global: industrial and intentional biological fixation of N			
	SDGs	- Nitrogen use efficiency in food systems - Phosphorus use efficiency in food systems			- Eutrophication of major estuaries	
Air pollution	LCA			- Intake fraction for fine particles (kg PM2.5-eq/kg)	- Human health damages	
	SDGs			- Mean urban air pollution of particulate matter (PM10 and PM2.5)	- [Mortality from indoor air pollution] – to be developed	
Ionizing radiation	LCA			- Human exposure efficiency relative to U^{235}	- Human health damages	
Photochemical ozone formation	LCA			- Tropospheric ozone concentration increase	- Human health damages	
Chemical pollution/ introduction of novel entities	LCA				- Ecosystem damages - Human health damages	
	PB	- No indicator currently defined. It may be for example chemical emissions, concentrations, or effects on ecosystem and earth system functioning				
	SDGs		- [Indicator on chemical pollution] – to be developed			

Impacts on		Drivers	Pressures	States	Impacts	Responses
Waste treatment	SDGs	- Proportion of the population connected to collective sewers or with on-site storage of all domestic wastewaters	- Percentage of urban solid waste regularly collected and well managed - Percentage of wastewater flows treated to national standards [and reused] – to be developed	- Global Food Loss Index [or other indicator to be developed to track the share of food lost or wasted in the value chain after harvest]		
Land system change	LCA			- Soil Organic Matter	- Ecosystem damages - Natural resource damages	
	SDGs	- [Ratio of land consumption rate to population growth rate, at comparable scale] – to be developed		- Annual change in degraded or desertified arable land (% or ha)		- [Indicator on the conservation of mountain ecosystems] – to be developed
Marine system change	SDGs			- Share of coastal and marine areas that are protected - Area of coral reef ecosystems and percentage live cover		- [Indicator on the implementation of spatial planning strategies for coastal and marine areas]– to be developed
Change in biosphere integrity /biodiversity	LCA			- Potential affected fraction of species	- Ecosystem damages	
	PB			- Extinction rate - Biodiversity intactness index		
	SDGs			- Genetic diversity of terrestrial domesticated animals - [Indicator on genetic diversity in agriculture] – to be developed - Red List Index - Living Planet Index - Abundance of invasive alien species		- [Indicator on global support to combat poaching and trafficking of protected species] – to be developed - Protected areas overlay with biodiversity
Freshwater use	LCA		- Water use related to local scarcity of water		- Natural resource damages	
	PB		- blue water use			
	SDGs	- [Crop water productivity (tons of harvested product per unit irrigation water)] – to be developed		- Proportion of total water resources used (MDG Indicator)		- [Indicator on water resource management] – to be developed - [Reporting of international river shed authorities on transboundary river-shed management] – to be developed
Forest resources	PB			- Area of forested land as % of original or potential forest cover		
	SDGs			- Annual change in forest area and land under cultivation (modified MDG Indicator) - Area of mangrove deforestation (hectares and as % of total mangrove area)		- Area of forest under sustainable forest management as a percent of forest area - Improved tenure security and governance of forests
Fish resources	SDGs			- Proportion of fish stocks within safe biological limits (MDG Indicator) - Percentage of fish tonnage landed with Maximum Sustainable Yield (MSY)		- Percentage of fisheries with a sustainable certification - [Use of destructive fishing techniques] - Indicator to be developed
Energy resources	SDGs	- Presence of urban building codes stipulating either the use of local materials and/or new energy efficient technologies or with incentives for the same - Rate of primary energy intensity improvement		- Primary energy by type - Share of energy from renewables		Fossil fuel subsidies ($ or %GNI)
Fossil and mineral resources	LCA			- Scarcity	- Natural resource damages	
Food and agricultural resources	SDGs		- Global Food Loss Index [or other indicator to be developed to track the share of food lost or wasted in the value chain after harvest]	- Crop yield gap (actual yield as % of attainable yield) - Cereal yield growth rate (% p.a.) - Livestock yield gap (actual yield as % of attainable yield)		

LCA indicators can also be applied to assess sustainability at larger scales, but uncertainties are expected to be high. PB, similar to LCA, is purely science-based indicator. But the boundary is set at the global level. Some extra efforts are needed to apply it on smaller scales. Meanwhile, PB provides good scientific support for political decisions related to environmental sustainability.

On the environmental impact pathway, Driver and Pressure indicators are closer to the cause than State indicators, while Impact indicators come the last. The closer to the cause, the less uncertainty there is in the models but also the more ambiguous the relation is to the consequences in terms of environmental sustainability. If the cause-effect chain is well established and the uncertainty can be reduced to an acceptable level, it can be very relevant to define improvement requirements at the Drivers level. However, if this is not the case, we may get perverted incentives where the Drivers are without leading to the desired changes in the States and Impacts. Which indicator on the DPSIR chain is more suitable for a specific purpose? The answer to this question depends both on the maturity of specific impact categories cause-effect chain and the decision context.

There are studies helping decision makers choosing the right sets of indicators. In the summary of criteria for selecting environmental indicators [15], the most commonly used criteria include "measurability, low resource demand, analytical soundness, policy relevance and sensitivity to changes within policy time frames". In addition, according to the Mutually Exclusive and Collectively Exhaustive (MECE) principle [16], the impact categories and indicators should be exhaustive, but also exclusive in the sense of avoiding overlaps of their impact pathways. The current impact categories and corresponding indicators may have some overlapping. For example, chemical pollution and air pollution may also have an impact on biodiversity and human health. Waste treatment may have some common indicators with freshwater use. Indicators in marine and land system change can be overlapped with biodiversity. These need to be treated carefully to avoid double counting when choosing the right sets of indicators for specific purposes.

5. Conclusions and perspectives

This study examines available environmental sustainability indicators in the methodological frameworks of LCA, PB and SDGs. LCA and PB have similar purposes to protect the earth as a whole in long terms. In contrast, SDGs also puts a strong emphasis on the social dimension of sustainability. Nevertheless, all studied indicator sets share a focus on seven environmental impact categories, including climate change, acidification, ozone depletion, eutrophication, chemical pollution, freshwater use, and change in biosphere integrity/biodiversity. Other impact categories are still under development (e.g. ecosystem changes and resource depletion). SDGs propose targets on them, but clearly more research is needed to establish the cause-effect chain and provide proper indicators in the future. We discussed several considerations when choosing the right indicator sets for a specific purpose. For example, LCA, PB and SDGs are suitable for application on product, global and section/national level respectively. The maturity of the cause-effect chain for each category is different. The uncertainty associated with each indicator depends both on the locations of that indicator on DPSIR chain and the maturity of the specific impact cause-effect chain that it belongs to. Which indicators to choose for a specific decision problem depend on its context (e.g. application scale, interested impact categories and study purpose) and its acceptable uncertainty level. Moreover, there are some indicators that may overlap with others, which should also be taken into account. The desired indicator sets should be decided in consultation with the decision-makers, but the decision should consider the aspects highlighted in the analysis here.

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